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PERMAFROST INVESTIGATIONS IN CANADA

BY

R. F. LEGGET, H. B. DICKENS, AND R. J. E. BROWN

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Permafrost Investigations in Canada

R. F. LEGGET, H. B. DICKENS,
AND R. J. E. BROWN

ABSTRACT

A knowledge of permafrost distribution is of vital concern to the practising engineer and geologist. The Division of Building Research is engaged in mapping permafrost in Canada on the basis of continuous and discontinuous zones. The information obtained to date has been compiled mainly from direct field observations and the mapping of permafrost by such methods is a long-term project. Recently the Division has initiated a study of climatic and terrain factors affecting the existence of permafrost in specific locations as a means of improving the ability to predict permafrost conditions. The basic energy factors affecting permafrost distribution cannot be measured with sufficient accuracy to determine the thermal condition causing permafrost which is the integrated effect of climatic and terrain factors over a long period. The objective of this study, therefore, is to investigate the thermal characteristics of the terrain components and to seek correlations between these, the climatic factors, and the distribution of perennially frozen ground.

ALMOST ONE-HALF OF THE LAND AREA of Canada is underlain by permafrost. This is the term now commonly used to describe that part of the earth's crust where the temperature is perennially below 0° C. (Bryan [1946] suggested terms that are more precise semantically but they have not been generally accepted in North America.) The existence of permafrost is of interest to both the earth scientist and the civil engineer. To the former, this phenomenon raises a number of puzzling geothermal questions; to the latter, it becomes a matter of vital concern wherever the frozen material is a water-bearing silt or clay because its presence can be fraught with serious consequences for engineering work. Figure 1 shows a typical result of neglect of necessary and well-recognized precautions when engineering construction disturbs permafrost conditions.

Appreciating the widespread existence of permafrost, the Division of Building Research of the National Research Council has been conducting investigations into permafrost since 1950 as part of its contribution to the progress of building in Canada. From both a practical and a scientific point of view, there arise two main questions: where may permafrost be encountered in Canada and why does the condition exist?

In its continuing search for answers to these questions, the Division has gathered information from a variety of sources including the technical literature, reports from others operating in permafrost areas, and from direct field observations. Emphasis has been placed on determining the southern limit of permafrost but observations from the entire permafrost region are also being recorded. Observations have been classified as indicating continuous or discontinuous permafrost defined on an areal basis as follows: *continuous* where permafrost is found everywhere in the region,

and *discontinuous* where permafrost exists in combination with some areas of unfrozen material. The discontinuous zone is one of broad transition between continuous permafrost and ground with a mean temperature which is above 0°C . In this zone, permafrost may vary from a widespread distribution with isolated patches of unfrozen ground to predominantly thawed material containing islands of material that remain frozen.

In Alaska (Benninghoff, 1952) and Russia (Baranov, 1955; Sumgin *et al.*, 1940; Tsytoich, 1958; Tumel', 1946) permafrost classifications have been made on the basis of temperature and thickness of the permafrost. Classification on a temperature basis has been greatly aided in the U.S.S.R. by the large number of ground temperature installations that have been made in permafrost regions and which have been used in preparing maps of permafrost distribution. In Canada, ground temperature observations in northern regions are still insufficient to delineate permafrost zones in this way. Enough information has been collected, however, to permit an approximate classification of permafrost on an areal basis (Figure 2). This collecting of information is continuing, facilitated by a permafrost questionnaire that has been prepared by the Division and which is now being circulated to appropriate groups throughout northern Canada.

Mapping the distribution of permafrost by such means is inevitably a long-term project. To improve accuracy in the prediction of the occurrence of permafrost, it is necessary to study the basic factors affecting its formation and continued existence. Permafrost exists as a result of a thermal condition which is reflected in a mean ground temperature that never rises above 0°C . The ground temperature pattern is complicated, varying with depth from the surface and with time. Because temperature is an index of the level of heat storage, it fluctuates in response to the

FIGURE 1. Soil flow resulting from thawing of perennially frozen silt under a road.

heat losses and heat gains at the ground surface. These follow a cyclical pattern on a daily as well as a yearly basis. The mean ground temperature will change over a given period of years only to the extent that the heat losses and heat gains for that period are unequal, the difference being reflected in a change in the mean level of heat stored in the ground. It follows that any extensive permafrost condition may develop over a very long period of time owing to a very small imbalance in annual heat losses and heat gains. A local permafrost condition may, however, be created or destroyed in a short period only if a relatively large imbalance between annual heat losses and heat gains has been created. To learn more about the occurrence of permafrost, attention must therefore be directed to the factors that determine the annual heat losses and heat gains at the ground surface. These factors may be grouped broadly under climate and terrain, the latter including ground thermal properties. They may not be readily separated in the over-all picture because of the interactions between them.

Across the upper boundary of the earth's atmosphere the energy gains by solar radiation may be regarded as constant, being balanced by a corresponding loss by radiation from the earth to outer space. The distribution of solar radiation at the earth's surface varies greatly, however, not only on a regular pattern—with time of day, time of year, and latitude—but also on a much more variable basis owing to absorption and scattering produced by the earth's atmosphere. Clouds, for example, may at times provide complete interception of direct solar radiation. Climate is produced by the radiation exchange that takes place between outer space, the

FIGURE 2. Distribution of permafrost in Canada.

atmosphere, and the earth's surface; this in turn both affects and is affected by the energy exchanges occurring at the surface of the earth itself.

The heat exchange at the ground surface is thus highly variable in respect of climatic factors, but it is also affected by terrain, or surface, conditions including the thermal properties of the ground itself, often referred to as the geothermal conditions. It is highly variable not only with time at any one point but may also be variable from point to point on the ground. It is necessary to examine this situation carefully in order to determine just what can usefully be done in predicting permafrost occurrences and possible changes in permafrost distribution.

PERMAFROST AND CLIMATE

Air Temperature

The climatic factor that is most readily measured and most directly related to ground heat loss and heat gain is the temperature of the air. Many investigators have estimated the mean annual air temperature required to produce and maintain a perennially frozen condition in the ground, but there is much disagreement on this matter. Terzaghi (1952) reported that the permafrost layer coincides very roughly with the 0°C mean annual temperature isotherm. In Canada, this is certainly not the case because this isotherm lies a considerable distance south of known areas of discontinuous permafrost. Black (1950) reported that the mean annual air temperature required to produce permafrost varies many degrees because of local conditions and suggested that it is generally between 24°F and 30°F . Nikiforoff (1928) in his hypothesis of the origin of permafrost suggested that the southern boundary coincides approximately with the -2°C isotherm.

In parts of Canada there is some similarity between the position of the 25°F mean annual isotherm and the southern limit of permafrost (Thomas, 1953). In the Yukon Territory, however, the 30°F isotherm lies much nearer the approximate southern limit. In Manitoba, the known limit of permafrost cuts diagonally from the 25°F to the 30°F isotherm. In Ungava the permafrost limit lies far north of the 25°F , except in Labrador where there appears to be some similarity between this isotherm and the permafrost limit.

Attempts have also been made to relate permafrost distribution in Canada with freezing (Wilkins and Dujay, 1954) and thawing indices but without much success. These indices reflect the annual fluctuation of air temperature about the freezing point and indicate the amount of heat added to and withdrawn from the ground. A station with a mean annual air temperature of 0°C will therefore have equal freezing and thawing indices. It can be shown that there is only a very broad relation between permafrost distribution and air temperature, and freezing and thawing indices. Accurate prediction of the occurrence of permafrost cannot be based solely on this climatic factor. It is therefore desirable to examine the ground heat exchange picture in more detail.

Heat Exchange Components

The short-wave solar radiation received at the earth's surface is broken up into a number of components, each causing a process in which heat transfer occurs (Figure 3) (Geiger, 1950; Thornthwaite and Hare, 1955). Some of the radiation

is reflected from the ground surface, the amount dependent on the reflectivity of the surface; some creates convection in the air resulting in a turbulent heat-exchange régime, some is used for evapotranspiration, and the remainder heats the ground. Heat is also carried into the ground by percolating rain and surface water.

In summer, the earth's surface gains heat from solar radiation by day and loses heat by outgoing radiation at night, the amount varying with the type of surface. In winter, the incoming radiation is reduced by day owing to the reduced angle of incidence of the sun's rays, their longer path through the atmosphere, and the shorter daily period of sunlight. North of the Arctic Circle there is a period in winter, varying directly in duration with latitude, when no radiation is received because the sun is below the horizon. The amount of incoming radiation reaching the earth may be reduced to a small quantity through reflection by clouds. The actual amount absorbed may be reduced substantially by snow cover. On a winter night the outgoing long-wave radiation is lowered owing to the reduced temperature of the earth's surface from which the heat must be drawn. Under conditions leading to a net loss outwards, the temperature of the ground surface may be reduced below that of the adjacent air and soil layers.

Incoming solar radiation and permafrost distribution are related only in a very general way. Permafrost areal extent and thickness increases generally with latitude as solar radiation decreases; examination of average daily incoming solar radiation on a horizontal surface over a two-year period (October 1957 to September 1959) bears this out.

At the earth's surface, the components of the heat exchange are affected by several factors (Swenson, 1956). The conduction-convection flux is affected by air movement and temperature. Radiation from the surface varies according to the

FIGURE 3. Diagrammatic representation of components of surface energy exchange.

TABLE I

Location	Latitude	Permafrost zone	Average daily radiation gm cal/cm ²
Ottawa	46° N	None	324
Winnipeg	50° N	None	319
Edmonton	54° N	None	296
Knob Lake	55° N	Sporadic	233
Fort Simpson	62° N	Sporadic	245
Aklavik	68° N	Continuous	223
Resolute	75° N	Continuous	210

reflectivity of the surface and weather conditions. When the sun is shining, there is a heat gain to the soil regardless of soil temperature. During overcast conditions, there can be a heat gain or loss and on clear nights there is a heat loss to the atmosphere from the ground. The evaporation-condensation flux is affected by the vapour pressure difference between the soil and the atmosphere and by air movement.

The annual heat-exchange equation at the earth's surface can be written as

$$R = LE + P,$$

where R is the annual radiation balance, LE the heat involved in evaporation-condensation, and P the heat involved in conduction-convection (turbulent heat-exchange) (Grigor'ev, 1958; Budyko, 1958). In any locality where the net radiation balance is known, it follows that an increase of heat transfer by evaporation decreases the amount in turbulent exchange and vice versa. Investigations in the U.S.S.R. show that the ratio of $P:LE$ at the tree-line is about 1:6 or 1:7 increasing to about 1:3 in the south-central part of the taiga where the permafrost boundary occurs.

For a period of one year's observations at Point Barrow, Alaska, where permafrost is continuous, and conditions approximating potential evapotranspiration were assumed to exist most of the time, Mathers and Thornthwaite (1956; 1958) found that the evaporative heat flux was about 40 per cent of the net radiation. This contrasts markedly with mid-latitude areas having moist soils where about 80 to 90 per cent of the net radiation is used in the evaporation of water. These investigators attributed the lower percentage of evaporation in the net exchange at Point Barrow to the presence of permafrost. It is interesting to note that the $P:LE$ ratio at Point Barrow was found to be 1:0.7 in contrast to the Russian figures of 1:6 or 1:7 at the tree-line.

Because of the short period of observation, Mathers and Thornthwaite could not say whether there were any significant variations in evapotranspiration from one site to another. Different vegetative covers do show variations in net radiation and it is possible, on the basis of the annual heat exchange equation, that different amounts of evapotranspiration might be expected with variations in turbulent heat exchange at these various surfaces. The energy exchange régime at the earth's surface consists of a number of different components. Each of these components can be measured, although instrumentation is often complicated and costly. It is clear, however, that climate factors alone do not completely determine the heat

exchange; surface and ground thermal characteristics must also be taken into account.

PERMAFROST AND TERRAIN

The effect of climate on the ground thermal régime shows marked variation with differences in ground surface conditions, either natural or man-made. These varying conditions generally arise from major differences in surface configuration, surface cover, and subsurface material. The thermal anomalies that they create have been examined to varying degrees by several workers. Only a brief review of these factors can be presented.

Configuration

The configuration of the ground surface, or the ground relief, determines the angle the ground surface makes with the horizontal and also the direction of its exposure with reference to the compass. Both these factors of slope and aspect affect the amount of solar radiation received by the surface. In zones of sporadic permafrost, this may result in permafrost occurring on north-facing slopes but not on adjacent slopes facing south. In continuous zones, the permafrost tends to be thicker and the active layer thinner on north-facing slopes. In hummocky tundra areas, the irregular permafrost table often appears as a mirror image of the ground configuration, owing to variation in solar radiation resulting from differences in microrelief (Tikhomirov, 1959). Slope and aspect may also have an influence on other factors such as air temperature, wind, and relative humidity. Another aspect of terrain is altitude. In itself, this can cause the occurrence of permafrost, even in temperate regions, owing to the reduction of air temperature with altitude.

Surface

The main types of surfaces that affect the ground thermal régime are vegetation, snow cover, water such as in lakes or rivers, bare soil, and rock.

Vegetation. The entire vegetative complex exerts an influence but it is the effect of plant cover such as mosses and lichen that appears to be paramount. The influence of a vegetative cover is not clearly understood but the suggestion that it provides resistance to heat flow by conduction only is almost certainly too simple a view. Vegetation contributes to evapotranspiration and thus a very considerable proportion of the solar radiation received can be rejected in this way without the soil beneath being affected. Mosses are strongly hygroscopic and are capable of losing moisture rapidly and in large quantities. Lichens, however, have been found to have extremely dry surfaces at times, even when lower layers near the soil are very wet. It may be that they are able to protect the soil against heat gain more by an insulating rather than an evaporative cooling effect, although some investigators have suggested that low soil temperatures and a high permafrost table are maintained by rapid evaporation at the wet basal layers.

Snow cover. Although snow is basically a climatic factor, it is more readily considered as a terrain factor for the purpose of this study, as snow cover is another type of surface that influences heat transfer between the air and the ground. As

with other terrain factors, exact knowledge of the effect of snow cover on the ground thermal régime is not yet available and is difficult to determine. Observations taken in the Ottawa area (Gold, 1958) indicate that the rate of heat flow from the ground in winter is inversely proportional to the snow depth but the general validity of this relation has not yet been verified. It is known that the presence of snow will reduce the depth of seasonal frost penetration in non-permafrost areas. It has been suggested that, other things being equal, it will do this by an amount equal to twice the thickness of snow cover. Conversely, the thawing of frozen soil in spring is inhibited by the snow cover.

Tikhomirov (1952) has shown that a thin snow cover does not prevent some solar radiation from affecting the underlying soil surface. He states that a snow cover 2 to 3 cm thick will pass 50 per cent of the solar radiation and that 10 cm and 50 cm of snow will pass 2 per cent and 1 per cent of solar radiation respectively. Lachenbruch (1959) has reported that at Point Barrow, a one-foot layer of packed, drifted snow over sandy gravel has raised the mean annual temperature of the ground surface by 3°C and at Umiat, 170 miles southeast of Point Barrow, the increase has been 4.5°C .

Water surfaces. The heat storage capacity of a body of water is much higher than that of land; the reflectivity of the surface to radiation is much lower. The reflectivity is determined by a number of factors, two of which are the roughness of the water and the altitude of the sun. Geiger (1950) gives average values of reflection from a water surface of 9 per cent of the visible spectrum and 5 per cent of the ultraviolet. These values are much lower than those cited for vegetation, snow cover, bare soil, and rock. The evaporation characteristics will also differ from other types of cover. As a result of these and other factors, a water surface results in an increased temperature in the ground beneath.

There is almost always a *talik*, or unfrozen zone, beneath bodies of water in permafrost areas. The extent of this thawed zone will vary with a large number of factors—the area and depth of the water body, the thickness of ice and snow cover in winter, the flow rate in the case of a river, and the general hydrology of a lake, as well as the composition of the bottom sediments and their history. An understanding of the thawing effect of water on permafrost is therefore of unusual importance to the engineer engaged in the design of reservoirs, dykes, and dams in northern regions.

The effects of rivers are the most difficult to assess because the energy exchange relationships are complicated by water movement. Brewer (1958a) reports a warming of 3°C to a depth of 135 feet in the soil underlying the Shaviovik River in Alaska, 200 miles east of Point Barrow. Grigor'ev (1959) showed that the moderating influence of rivers on the permafrost extended a distance of 100 m away from the river bank and produced thawed layers beneath the river up to 30 m thick. He concluded that these thawed zones generally take the form of an extended trough, the width of which is proportional to the width of the river.

In the case of lakes, it has generally been assumed that, for those that do not freeze to the bottom, the thickness of the unfrozen layer beneath is proportional to the lake diameter, and that there will be no permafrost beneath, for lakes the widths of which exceed the normal thickness of permafrost in the area. Recent

Russian observations in Siberia have suggested, however, the importance of the geologic structure of the lake bottom upon heat flow and hence on the extent of the *talik* (Grigor'ev, 1959). Impermeable sediments restrict convective heat exchange at the lake bottom. In such cases it has been suggested that the thickness of taliks beneath lakes that do not freeze to the bottom will be proportional to the yearly temperature amplitude of the region regardless of the areal extent of the lake.

An important factor in the thermal effect of lakes on the permafrost below is the tendency of water at 4° C (the temperature at which it has its highest density) to accumulate at the lake bottom, and the corresponding elimination of convective action as the lake cools below this temperature. It may also be postulated that a lake, which is replenished by run-off from a drainage basin in summer, benefits from heat collected from that area by the water that will normally flow at temperatures well above freezing.

Although lakes deep enough to maintain some unfrozen water during all seasons have the greatest thawing effect on permafrost, even shallow lakes which freeze completely in winter modify the thermal régime of the permafrost below. Brewer's (1958b) studies of lakes in the Point Barrow region of Alaska showed the mean permafrost temperatures beneath these lakes to be up to 3° C higher than in the surrounding undisturbed terrain. This study showed also that lakes having a diameter of half a mile or more and a depth of at least seven feet could be expected to have basins unfrozen to a depth of 200 feet.

The influence of a very large body of water such as the ocean has been examined by Lachenbruch (1957) who cites the increase in geothermal gradient evidenced in the studies at Resolute Bay, Northwest Territories, as an example of the ocean's effect. He suggests that this change is an indication of the length and rate of emergence of the land.

Soil and rock surfaces. As surfaces, soil and rock have considerable influence upon reflectivity to solar radiation. Reflectivity values in the range of twelve to fifteen for rock (Ångström, 1925) and fifteen to thirty for tilled soil (Geiger, 1950) have been given. There will also be different evaporation rates and intakes of precipitation. The latter effects border on ground thermal problems and are difficult to differentiate from the properties discussed in the following sections.

Ground Thermal Properties

The thermal properties of the ground itself have a marked influence on the net heat exchange and resulting temperatures, supplementing the influences of climatic and terrain factors as already discussed. In the simplest cases, involving only transient heat flow by conduction, the thermal diffusivity of the soil becomes important in determining the rates at which heat is transferred from the surface into the soil itself. This affects the surface temperatures, which influence, in turn, the surface heat exchange rate. For example, soils that warm up quickly under solar radiation will achieve high-surface temperatures that can result in a substantial loss of heat by conduction-convection, thus affecting the over-all heat gain (Landsberg and Blanch, 1958). Thus the thermal conductivity, density, specific heat, and moisture content of soil all have an influence on its thermal régime.

Unfortunately, the transfer of energy through actual soils is often greatly com-

plicated by their variability, and by the presence of moisture, particularly when a change to the vapour state is involved. When permafrost is present there are further complications in such thermal calculations because of the differences in properties between frozen and unfrozen soils as well as of the latent heat of fusion released when water is frozen. This is not readily taken into account by the heat-conduction theory.

RELATED EXPERIMENTAL WORK

Many of these factors affecting the occurrence of permafrost are also of importance in the study of the ground thermal régime in non-permafrost areas. Much of the work of the Division of Building Research on frost action, ground temperatures, and heat flow in southern regions is consequently of direct relevance to the permafrost problem.

One of the Division's earliest projects in this general field was the study of ground temperatures. This involved the direct field recording of soil temperatures at many locations in both permafrost and non-permafrost areas and under a wide variety of natural conditions (Crawford and Legget, 1957). These studies have provided information on the effect on ground temperatures of air temperature, soil type, and snow cover. An analysis of some of the observations has suggested that simple heat-conduction theory can be used to describe certain long-period temperature variations that occur within the soil (Pearce, 1958b) in the range of annual temperature variation.

Closely paralleling these studies of the natural ground thermal régime are investigations of the effect of man-made structures on ground temperatures. A cold storage plant, in which the ground beneath was subjected to freezing during operation of the building, presented the reverse situation to the thawing problem that arises in permafrost regions under heated structures (Pearce and Hutcheon, 1958; Pearce, 1958a). Other soil temperature studies have dealt with the problem of freezing water-mains and have included observations on the water and sewage installations in the permafrost area of Yellowknife (Legget and Crawford, 1952; Copp *et al.*, 1956). Variations in soil temperatures under small, heated test structures have also been examined (Solvason and Handegord, 1959). Observations are being made beneath dykes under construction at the site of a new hydroelectric plant in an area of discontinuous permafrost.

Much emphasis has been placed on the study of frost action in soils, chiefly in relation to the basic mechanism itself (Penner, 1956; Penner, 1957) but also with respect to the correlation of frost action damage with the main climatic factors (Crawford and Boyd, 1956). It seems probable that this same frost action mechanism is involved in the formation of many of the ice structures encountered in permanently frozen soil. It may have been a determining factor in the formation, on a long-term basis, of some of the more prominent surface manifestations of permafrost such as pingos, frost medallions, and some types of patterned ground.

The Division has also studied the effect of moisture upon heat transfer in porous materials to try to improve understanding of the heat transfer mechanism in moist soils (Woodside and Cliffe, 1959; Woodside and DeBruyn, 1959). The role of moisture in heat transfer at the ground surface has been examined in terms of

evaporation from both snow (Williams, 1959a) and water surfaces (Williams, 1959b). The latter study was concerned with the improvement of empirical methods of estimating heat losses from open-water surfaces and has shown that the total heat loss or gain can be correlated with the difference between mean sol-air and mean surface-water temperature.

Since 1953, the Division has conducted evapotranspiration observations at Norman Wells for another agency interested in verifying the Thornthwaite formula for potential evapotranspiration in relation to climate. These observations, as well as measurement of radiation factors, have recently been extended by the Division to local vegetative cover as a first step in the study of the effect of such cover on the basic energy components at the ground surface.

This brief summary of reports on related work carried out or in progress by the Division of Building Research is included to show that "permafrost problems" are not isolated scientific curiosities. Permafrost is a natural phenomenon, the study of which demonstrates that the solution even to the single problem of determining its extent is allied to many more general geotechnical problems.

DISCUSSION

The thermal properties of the earth's interior are still not completely understood. Enough is known, however, in this branch of geophysical study to be reasonably certain that the condition of permafrost is due to the cumulative effect of the thermal régime at the surface of the polar regions of the earth during the Recent geological period. It is known, for example, that the rate of heat-flow from the central core of the earth is so slow that its effect at the surface is of minor significance. Careful study of long-term records of (relatively) deep ground temperatures, now fortunately being obtained at a number of locations, should indicate eventually the approximate rate at which permafrost is degrading. The complications caused by the several climatic and terrain factors herein discussed make it impossible to investigate theoretically this aspect of permafrost with any degree of accuracy.

The mapping of permafrost, and especially of its southern boundary, must, however, be pressed forward, in Canada as elsewhere. Accurate determination of mean ground temperature is clearly the most certain method of determining the existence of permafrost. Unfortunately, the direct determination of mean ground temperatures is difficult to carry out under the conditions existing over most of northern Canada, so that coverage of the area with a pattern of temperature determinations would be extremely slow. The taking of observations is complicated by the annual temperature cycle so that temperatures must either be taken at some depth at which the annual variation is suitably damped, or a large number of shallow observations must be made over suitably spaced time intervals so as to provide a good average.

The making of direct observations of permafrost occurrences can be somewhat less involved, particularly because many opportunities for observation occur incidental to other work, such as the carrying out of construction projects. The distinction between permafrost and seasonal frost may sometimes be difficult to make. As in the case of the ground temperature approach, it may not be easy to

determine whether the observation made is typical of the area, without some considerable extension of the pattern of observations.

(It becomes important to know as much as possible about the factors that influence the ground thermal régime, many of which have been discussed here. Only with some knowledge of them will it be possible to begin to assess critically the limited observations on permafrost occurrence, and to use these with confidence in making predictions about adjacent areas. Some of this knowledge may also be valuable in assessing the effects that occur as man-made structures create changes in the ground thermal pattern.)

There is no justification for assuming that natural ground temperatures, and particularly the occurrence of permafrost, can be predicted directly from estimated ground heat losses and heat gains. The relatively poor accuracy with which such estimates can be made, even under the best of conditions, precludes the possibility that any summation of them over a long period is of specific use in this way. Prediction will be possible only by using, as a datum, some known or measureable factor that is closely related to and correlates with the perennially frozen condition. It should then be possible to make corrections that could be applied to the ground temperature condition inferred from the measured or known base quantity and arrive at improved prediction.

The choice of reference factors is limited. Only a few climatic factors are regularly measured over the area of interest. Of those factors that are measured, mean air temperature would appear to be by far the most suitable. It shows some general correlation with mean ground temperature, as indicated by the correspondence between certain isotherms and the permafrost boundary, as well as by other evidence. The differences between mean air and mean ground temperature are not usually great. The identification of the factors responsible for these differences and the establishment of quantitative relations is a formidable but not impossible task.

Recognition of the complexity of permafrost and identification of the major factors affecting its occurrence provide at least a starting point for further progress. Discussion of these factors has constituted the main part of this paper rather than a recital of field studies of permafrost in Canada already made by the Division of Building Research and other Canadian agencies. It has been by the critical study of the results of such field work, and of the select bibliography available (in which contributions from the U.S.S.R. are outstanding) that the discussion herein presented has been developed. Field work at the sites of engineering undertakings in the Canadian north, and in special test areas with typical permafrost conditions, is continuing. Results thus obtained will be assessed in the light of the factors herein outlined, and in relation to other geotechnical investigations such as those noted earlier, in a continuing endeavour to delineate, understand, and explain the occurrence of permafrost in Canada.

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REFERENCES

- ÅNGSTRÖM, A. 1925. The albedo of various surfaces of ground; *Geog. Annaler*, vol. 7, pp. 323-42.
- BARANOV, I. YA. 1955. Yuzhnaia granitsa oblasti rasprostraneniia mnogoletnemerzlykh porod *Materialy K Osnovam Ucheniia O Merzlykh Zonakh Zemnoi*, vol. II, pp. 38-44.
- BENNINGHOFF, W. S. 1952. Interaction of vegetation and soil frost phenomena; *Arctic*, vol. 5, no. 1, pp. 34-44.
- BLACK, R. F. 1950. Permafrost; *Smithsonian Report*, pp. 273-301.
- BREWER, M. C. 1958a. Some results of geothermal investigations of permafrost in northern Alaska; *Trans. Amer. Geophys. Un.*, vol. 39, no. 1, pp. 19-26.
- 1958b. The thermal régime of an arctic lake; *Trans. Amer. Geophys. Un.*, vol. 39, no. 2, pp. 278-84.
- BRYAN, K. 1946. Cryopedology—the study of frozen ground and intensive frost action with suggestions on nomenclature; *Amer. J. Sci.*, vol. 244, pp. 622-42.
- BUDYKO, M. I. 1958. The heat balance of the earth's surface; Office of Climatology, U.S. Department of Commerce.
- COPP, S. C., CRAWFORD, C. B., and GRAINGE, J. W. 1956. Protection of utilities against permafrost in northern Canada; *J. Amer. Water Works Assoc.*, vol. 48, no. 9, pp. 1155-68 (NRC 4056).
- CRAWFORD, C. B., and BOYD, D. W. 1956. Climate in relation to frost action, Highway Research Board, Bull. no. 111, pp. 63-75 (NRC 3746).
- CRAWFORD, C. B., and LEGGET, R. F. 1957. Ground temperature investigations in Canada; *Engineering J.*, vol. 40, no. 3, pp. 1-8 (NRC 4302).
- GEIGER, R. 1950. The climate near the ground; Harvard University Press.
- GOLD, L. W. 1958. Influence of snow cover on heat flow from the ground—some observations made in the Ottawa area; *Extrait des Comptes Rendus et Rapports*, Assoc. Internationale Hydrol. Sci., U.G.G.I., Toronto, 1957, IV, pp. 13-21 (NRC 4827).
- GRIGOR'EV, A. A. 1958. O nekotorykh geograficheskikh zakonomernostiakh teploobmena i vodoobmena na poverkhnosti sushi i o putiakh dal'neishego izucheniia obmena veshchestv i energii v geograficheskom srede; *Izvestiia Akad. Nauk SSSR, Seriya Geograficheskaiia*, no. 3, pp. 17-21.
- GRIGOR'EV, N. F. 1959. O vliianii vodoemov na geokriologicheskie usloviia primorskoii nizmennosti Ust'—Ianskogo raiona Yakutskoi ASSR; *Materialy Po Obshchemu Merzlotovedeniiu*, VII, Mezhdudovomstvennoe Soveshchanie Po Merzlotovedeniiu, pp. 202-6.
- LACHENBRUCH, A. H. 1959. Periodic heat flow in a stratified medium with application to permafrost problems; *U.S. Geol. Surv., Bull.* 1083-A.
- 1957. Thermal effect of the oceans on permafrost; *Bull. Geol. Soc. Amer.*, vol. 68, no. 11, pp. 1515-30.
- LÄNDSBERG, H. E., and BLANCH, M. L. 1958. Interaction of soil and weather; *Soil Sci. Soc. Amer.*, vol. 22, pp. 491-5.
- LEGGET, R. F., and CRAWFORD, C. B. 1952. Soil temperatures in water works practice; *J. Amer. Water Works Assoc.*, vol. 44, no. 10, pp. 923-39 (NRC 2910).
- MATHER, J. R., and THORNTHWAITE, C. W. 1956. Microclimatic investigations at Point Barrow, Alaska, 1956; *Publications in Climatology*, Drexel Institute of Technology, Laboratory of Climatology, Centerton, N.J., vol. IX, no. 1.
- 1958. Microclimatic investigations at Point Barrow, Alaska, 1957-1958; *Publications in Climatology*, Drexel Institute of Technology, Laboratory of Climatology, Centerton, N.J., vol. IX, no. 2.
- NIKIFOROFF, C. 1928. The perpetually frozen subsoil of Siberia; *Soil Sci.*, vol. 26, pp. 61-78.
- PEARCE, D. C. 1958a. An analysis of frost action beneath cold storage warehouses; *Trans. Engineering Inst. Canada*, vol. 2, no. 4, pp. 153-6 (NRC 5095).
- 1958b. Ground temperature studies at Saskatoon and Ottawa; *Extrait des Comptes Rendus et Rapports*, Assoc. Internationale Hydrol. Sci., U.G.G.I., Toronto, 1957, IV, pp. 279-90 (NRC 4796).
- PEARCE, D. C., and HUTCHEON, N. B. 1958. Frost action under cold storage plants; *Refrigerating Engineering*, vol. 66, no. 10, pp. 3-7 (NRC 4939).
- PENNER, E. 1956. Soil moisture movement during ice segregation; Highway Research Board, Bull. 135, pp. 109-18 (NRC 4278).
- 1957. The nature of frost action; *Proc. Thirty-Eighth Convention of the Canadian Good Roads Assoc.*, pp. 234-43 (NRC 4627).

- SOLVASON, K. R., and HANDEGORD, G. O. 1959. Soil temperature measurements at Saskatoon; Trans. Engineering Inst. Canada, vol. 3, no. 2, pp. 67-73 (NRC 5344).
- SUMGIN, M. I., KACHURIN, S. P., TOLSTIKHIN, N. I., and TUMEL', V. F. : 1940. Obshchee merzlotovedenie; Akad. Nauk SSSR.
- SWENSON, E. G. 1956. Weather in relation to winter concreting; RILEM Symposium, session A, general report no. 8575 (NRC 3830).
- TERZAGHI, K. 1952. Permafrost; J. Boston Soc. Civil Engineers, vol. 39, pp. 1-50.
- THOMAS, M. K. 1953. Climatological atlas of Canada; Division of Building Research, National Research Council, and Meteorological Division, Department of Transport (NRC 3151).
- THORNTWHAITE, C. W., and HARE, F. K. 1955. Climatic classification in forestry; Unasylva, vol. 9, no. 2, pp. 50-9.
- TIKHOMIROV, B. A. 1959. Vliianie rastitel'nosti na letnee protaivanie pochvy v oblasti mnogoletnemerzlykh porod; Materialy Po Obshchemu Merzlotovedeniiu, VII, Mezhdumestvennoe Soveshchanie Po Merzlotovedeniiu, pp. 207-9.
- 1952. Znachenie mokhovogo pokrova v zhizni rastenii krainego severa; Botanicheskii Zhurnal, vol. 37, pp. 629-38.
- TSYTOVICH, N. A. 1958. Osnovaniia i fundamenty na merzlykh gruntakh; Akad. Nauk SSSR.
- TUMEL', V. F. 1946. Karta rasprostraneniia vechnoi merzloty v SSSR; Merzlotovedenie, t. 1, no. 1, pp. 5-11.
- WILKINS, E. B., and DUJAY, W. C. 1954. Freezing index data influencing frost action; Proc. Seventh Canadian Soil Mechanics Conference, December 10-11, 1953, Associate Committee on Soil and Snow Mechanics, National Research Council, Canada, Tech. Mem. no. 33, pp. 36-9.
- WILLIAMS, G. P. 1959a. Evaporation from snow covers in eastern Canada; Division of Building Research, National Research Council, research paper no. 73 (NRC 5003).
- 1959b. An empirical method of estimating total heat sources from open water surfaces; Presented to Seminar on Ice Problems, Eighth Congress of the International Association of Hydraulic Research, Montreal, August 1959.
- WOODSIDE, W., and CLIFFE, J. B. 1959. Heat and moisture transfer in closed systems of two granular materials; Soil Sci., vol. 87, no. 2, pp. 75-82 (NRC 5030).
- WOODSIDE, W., and DE BRUYN, C. M. A. 1959. Heat transfer in a moist clay; Soil Sci., vol. 87, no. 3, pp. 166-73 (NRC 5098).